AIRFLOW AROUND SOME NEW ZEALAND DIVARICATING PLANTS

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ABSTRACT

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This study investigates the airflow patterns around four types of divaricating shrubs with differing branch structures. The plants were: *Coprosma cheesemanii* (45° branched), *Pittosporum obcordatum* (right-angle branched), *Myrsine divaricata* (weeping-branched), and *Corokia cotoneaster* (zigzag-branched). The project involved visualisation and measurement of the airflow patterns and wind velocities about simple and more complex models of the shrubs, as well as live specimens. From the visualisation of models based on cross-sections of the shrubs, there appeared to be calm zones, with reduced wind velocities, within their branch arrangements. Overall increases in complexity in the flow patterns and turbulence were seen as the wind speed increased up to 16 ms^{-1}. Densely branched shrubs (such as *C. cheesemanii* and *C. cotoneaster*) produced significantly more calmer zones; while regularly branched shrubs (such as *M. divaricata* and *P. obcordatum*) produced regularly spaced airflow patterns coinciding with their branches. These results could imply that densely branched shrubs have more favourable environments for growth of new leaves, flowers and fruit because of the lesser velocities. The drop in local wind velocity will also reduce convective transfer coefficients, thus affecting water loss. Further study is needed before firm conclusions can be made about transpiration rates within the branch network.

KEYWORDS: Divaricating - wind velocity - branch structure - turbulent flow.

INTRODUCTION

This project applies some physical principles to the understanding of airflow patterns around indigenous New Zealand, small-leaved, divaricating shrubs. Around 10% of all the woody species of plants in New Zealand are small-leaved and divaricating, having branches at relatively obtuse angles. This group includes shrubs and climbers which remain permanently divaricate and those which are divaricate and small-leaved only in juvenile forms. The term divaricating, according to the Concise Oxford Dictionary, refers strictly to branching that diverges or separates widely. Since the divaricating shrubs' branches continue to grow in a regular fashion, with uniform internodal distances, these species form very twiggy plants with fairly confined air-spaces within the shrub canopy.

Over the years there has been much speculation and hypothesising about the evolution of divaricating plants. Two main theories have advanced. The first proposes that the plants evolved the divaricating trait through selection by moa browsing. The second postulates that extreme climate conditions, both experienced currently and during the Pleistocene ice ages, have resulted in the plants growing in a divaricating manner as a means of climate protection. Although the moa-browsing hypothesis has prompted further study and debate on the topic, the overall argument seems to favour the climate hypothesis (McGlone & Webb 1981, Kelly & Ogle 1990, Wilson & Galloway 1993). A further general problem is the question why the divaricating habit should be so prominent in New Zealand when similar climatic conditions exist elsewhere.

By studying the airflow patterns through and around divaricating shrubs, the general features of the internal environment within the

shrub canopy can be determined. A local reduction in wind velocities inside the canopy could cause two effects. A reduction in wind would influence transpiration and cooling rates, with possible local increase in relative humidity resulting from the slower air exchange; or the reduction of wind might favour increased survival of leaves, flowers and fruit.

FLOW AROUND OBJECTS

The nature of the flow of air at a wind speed of u around an object with a characteristic dimension D is determined by the value by a dimensionless number known as the Reynolds number, Re, where,

$$Re = Du / v \quad \text{.....(1)}$$

in which v is the kinematic viscosity of the air and is a measure of its inherent stickiness and ability to damp out turbulence. In the case of a branch subject to a cross-flow of wind, the dimension D would be the branch diameter.

The Reynolds number represents a ratio of the internal forces, associated with the wind flow, to the viscous forces or friction of the fluid in hindering the movement. If the Reynolds number is low (around 1), the fluid is very sticky and the flow is laminar. As the Reynolds number increases, the fluid flow becomes more inertial in character and a wake eventually develops behind the object (Yang 1989). The boundary layer for the incident flow thickens around the object and ultimately the flow is sufficiently retarded for a reverse flow or wake to form at about Re = 17. Initially, the wake is a steady toroidal vortex, but above a Reynolds number of 65 a noticeable shedding of vortices occurs, with the formation of a so-called vortex street, the frequency of shedding being a function of the Reynolds number (Goldstein 1938). The development of a wake is illustrated in Figure 1 for cross-flow around a cylindrical object, like a branch.

Divaricating shrubs typically have branch diameters between 1 and 10 mm in size. In a moderate breeze of 15 ms^{-1} at 20°C, the Reynolds numbers would range correspondingly from 100 to 1000. The branch network is likely to generate a complex set of vortices as the air tries to stream through the matrix of branches.

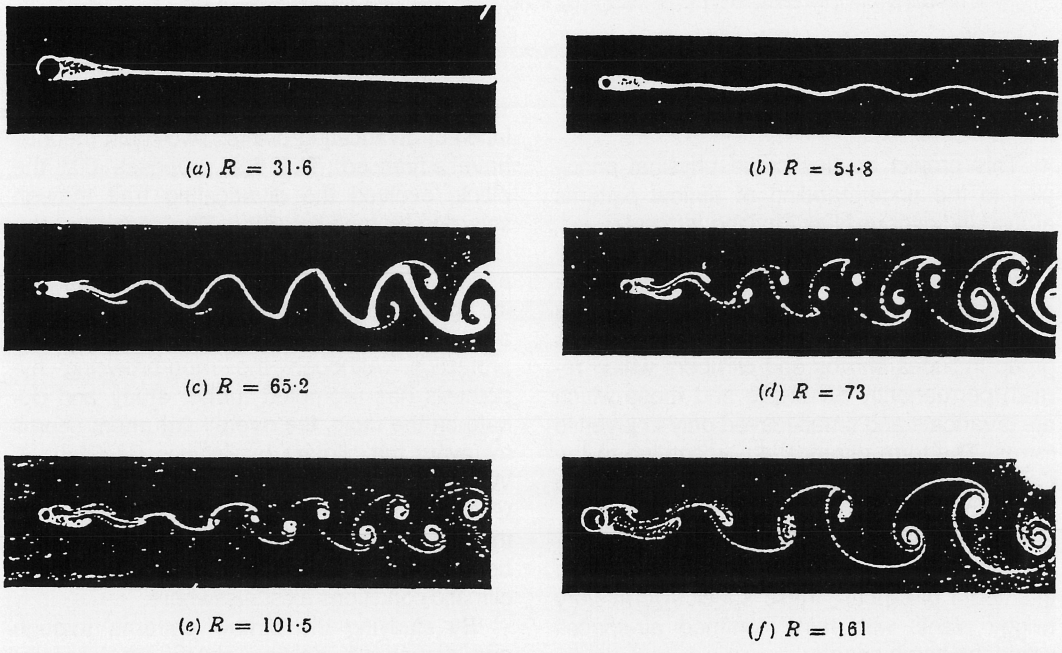


Figure 1. Flow patterns around a circular cylinder in cross-section at differing Reynolds Numbers. Plate 32 from Goldstein (1938).

Any airflow patterns around an object can be seen with the eye by using smoke to trace streamlines and turbulent eddy paths or by attaching micro-tufts to the object's surface whenever the wind velocity is so large that the smoke is dispersed too thinly for observation. A micro-tuft is a 30 mm long, fluorescent thread that has one end attached to a section of the body under examination. The movements of the unattached end of the thread indicate whether the airflow moving around it is laminar or turbulent. (The thread flaps furiously under turbulent conditions, while in laminar flow it remains almost stationary and aligned in the flow direction).

The aim of this study was to gain some insight on the role the wind played in influencing the growth of native divaricating plants by using simple models and actual small plants.

The specific objectives of this present study were to:

(1) investigate the airflow patterns around simple shrub models of increasing complexity including actual divaricating plants,

(2) obtain physical measurement of the airflow patterns seen, and

(3) determine the differences in airflow patterns caused by the differing branch structures of each plant from the visualisations and the velocity measurements.

MATERIALS AND METHODS

PLANT MATERIAL AND MODELS

The four species of shrubs used in this study were chosen for their differing branching structures, to ascertain the effect of branch architecture on the wind patterns. Two species were regularly branched: *Coprosma cheesemanii* (45° branching), *Pittosporum obcordatum* (right-angled branching); two more were irregularly branched: *Myrsine divaricata* (weeping-branching) and *Corokia cotoneaster* (zigzag-branching).

The plant specimens were young, potted, nursery-grown plants obtained from a North Canterbury source, about 0.2 m in height. Branch diameters varied between 1 mm and 7 mm, with internodal distances ranging from about 10 mm to 100 mm. The estimated Reynolds numbers are in a range of 225 to 7140 for typical Christchurch wind speeds (4 ms^{-1} to 16 ms^{-1}). Therefore highly turbulent wakes with shedding vortices are expected to form behind the branches. However, the subsequent flow is further interrupted by the intricate array of branches behind those facing the incident flow. Thus the wake pattern from a given individual branch is likely to merge with others to produce a complex flow regime within the whole branch network.

All the plants were small-leaved ($\leq$ 2 mm long), and the effect of the leaves on the overall airflow pattern is considered to be negligible. Three-dimensional models of the shrubs were built from "branches" of pipe cleaners on a wire stem and were based on a section of each of the actual live shrubs (Fig. 2). These models were built to full scale with the branch thickness being approximately the same as the shrubs. Two-dimensional models, used early on in the flow visualisation together with preliminary wooden models, were also built using pipe cleaners. Both the wooden and the two-dimensional models were around one-fifth of the actual plants' full height.

AIRFLOW VISUALISATION

This stage was completed in two parts. In the initial experiments, smoke (from an aerosol generator) was blown around the wooden blocks and the two-dimensional pipe cleaner models at low wind speeds to reproduce the airflow patterns around solid shapes that had been recorded previously (Goldstein 1938, Brauer & Mewes 1971, Clift *et al.* 1978, Yang 1989, Lee 1990, Kho 1992). The primary experiments extended the initial visualisation to include higher wind velocities, (similar to what the plant would normally be exposed to in the open) and the three-dimensional models and real plants.

All the experimental work was carried out in wind-tunnels at the School of Engineering, University of Canterbury, where the velocity and gustiness of the wind could be strictly controlled. For the preliminary visualisation, a small wind-tunnel was used (330 mm height), and the wind speeds ranged from 0.6 to 2 ms^{-1}. In the primary visualisation, an industrial wind tunnel was used (1 m height) with wind speeds of 4, 8, 12, and 16 ms^{-1}, which span the average wind speeds of 6.9 to 7.8 ms^{-1} recorded in 1995 at Christchurch.

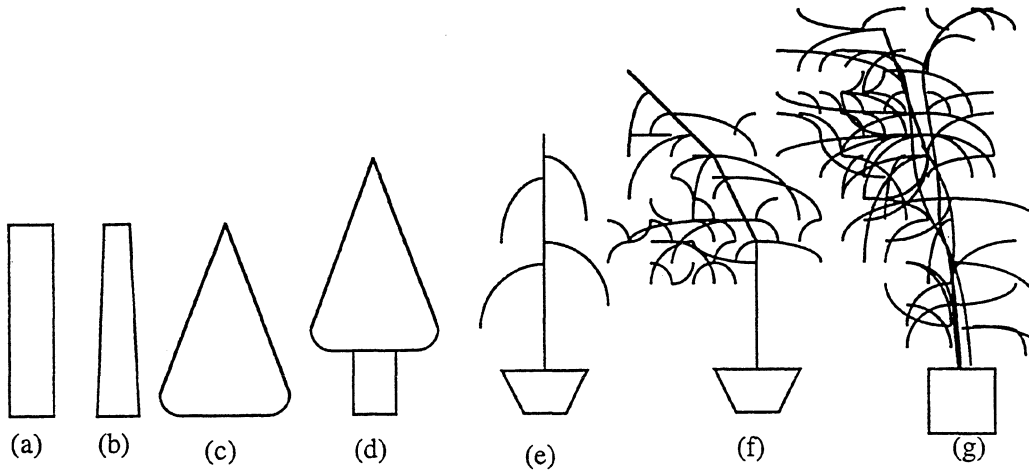


Figure 2. Model development for the *Myrsine divaricata* shrub starting with wooden models through to two and three-dimensional pipe cleaner models and finally to the shrub itself. The preliminary visualisation covers all the wooden models (a to e) and a cross-section of the two-dimensional pipe cleaner model, while the primary visualisation starts with the two-dimensional model and continues past the three-dimensional model through to the actual shrub (e to g).

WIND VELOCITY MEASUREMENT

Velocity measurements were carried out through a cross-section of the three-dimensional models (for each type of shrub) at average incident wind speeds of 4 and 8 ms^{-1} (above 12 ms^{-1} the models did not accurately represent the behaviour of the shrubs). A Dantec hot-wire anemometer (type: 9054 N 0601) was used to measure the wind speeds separately in directions parallel (x) and perpendicular (y) to the wind-tunnel floor, over a cross-section of each of the models, at intervals of 50 mm in each direction.

Figure 3 illustrates, by way of example, the array of anemomenter sampling points for measurements about a three-dimensional model of *M. divaricata*. The root-mean-square velocity components in both the horizontal (x) and the vertical (y) direction were recorded.

RESULTS

AIRFLOW VISUALISATION

From the airflow visualisation around three-dimensional models of the shrubs, calmer zones of lower velocities (micro-climates) could be seen within the central regions of the branches. These calmer zones remained noticeable even at the higher speeds of 12 and 16 ms^{-1} that were examined. Figure 4 illustrates the micro-tuft visualisation of flow past the model of *M. divaricata*, showing laminar flow within the branches and turbulent flow at the branches extremities, for wind speeds of 4 to 16 ms^{-1}.

The actual *M. divaricata* plant seemed more responsive to the wind than the three-dimensional model. At wind speeds of 12 ms^{-1} or greater, the actual plant bent over more in the wind. However, this behaviour may be atypical of more mature plants in the field, since the specimens used in the wind-tunnels were young, flexible, nursery-grown plants.

Further it was observed during these wind-tunnel tests that several minutes were needed after the airflow had been shut off before the live plants returned to their usual position or "recovered" from these wind speeds. This length of recovery time was proportional to the time it took the wind decay after the wind-tunnel fan was shut down, and not directly to the magnitude of the wind-speed itself, as had been anticipated.

WIND VELOCITY MEASUREMENT

The wind velocity measurements, through a cross-section of the shrub models, showed diminishing wind velocities within the branches

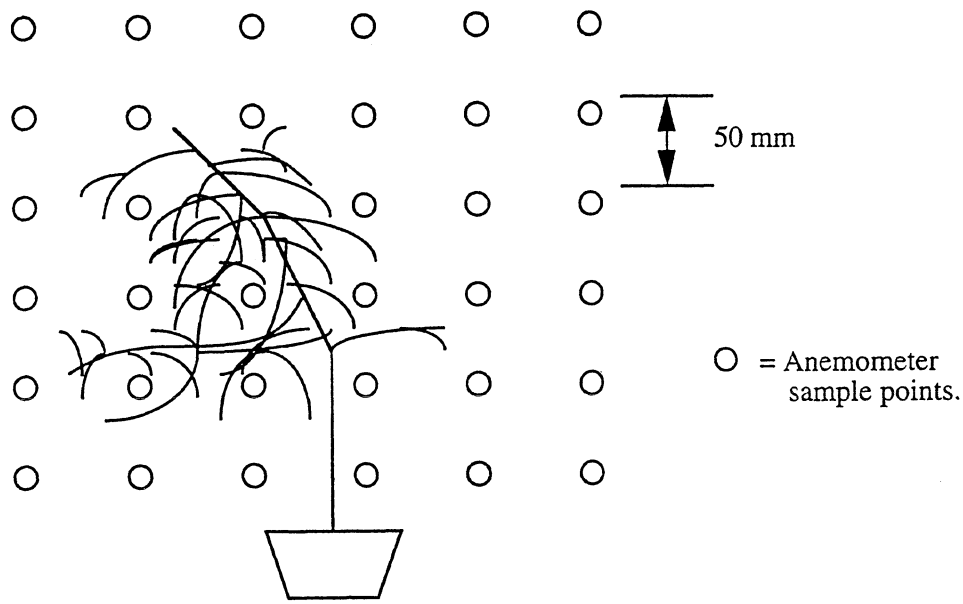


Figure 3. A pictorial representation of velocity measurement positions through a cross-section of the *Myrsine divaricata* three-dimensional pipe cleaner model.

of the shrubs. Several trends emerged. First, the patterns seen at the lowest velocity of 4 ms^{-1} became more exaggerated and enhanced at a higher velocity of 8 ms^{-1}. At this higher wind velocity, there is a greater overall relative decrease in the magnitude of the airflow velocities parallel to the wind-tunnel floor and, in particular, an increase in airflow turbulence in the direction perpendicular to the wind-tunnel floor. These changes are accompanied by an increase in the complexity of the airflow pattern, as revealed in the topographical charts which are shown in Figure 5. A similar trend towards more complex (and turbulent) behaviour was revealed by the greater amplitude of micro-tuft oscillations in the visualisation tests as the velocity itself was increased.

Several more trends emerged in comparing the patterns from all the shrubs. If a shrub had a higher branch density (in a unit volume), then there were lower overall wind velocities within the branches than in a less densely branched shrub. This difference can be seen in Figure 6, which illustrates the velocity fields shown as surface charts for the densely branched *C. cheesemanii* model and for the less densely branched *P. obcordatum* model.

The branch structure appears to influence the form of the calmer zones within a divaricating shrub. Irregular branched shrubs (like the zigzag architecture of the *C. cotoneaster* featured in Figure 7, or the weeping branches of the *M. divaricata*), produce more random airflow patterns. A regularly branched shrub (like the 45° branching of the *C. cheesemanii* or the right-angle branching of the *P. obcordatum*) produce regularly spaced patterns, reflecting the position of their branches, with reductions up to 75% of the incident airflow velocity.

Figure 7 shows a sinusoidal wave-front moving up through the branches of the *C. cheesemanii*. The troughs of the front correspond to the locations of the branches. A similar pattern could also be seen in the flow through the *P. obcordatum*, which also had regularly spaced branching. As Figure 7 is a surface chart of velocities vertically, an indication of turbulence within the plants can be seen. The undisturbed normal velocity profile

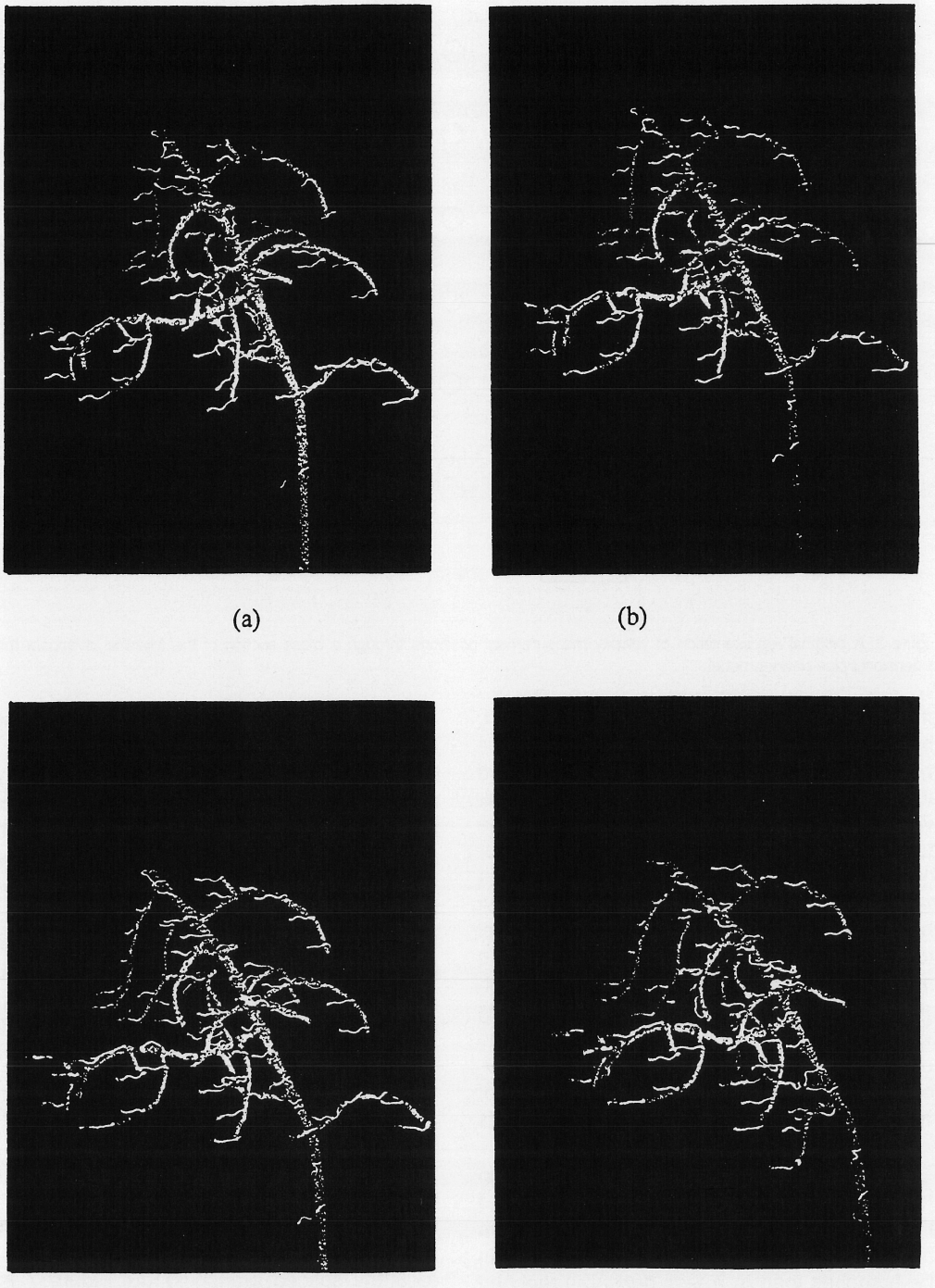
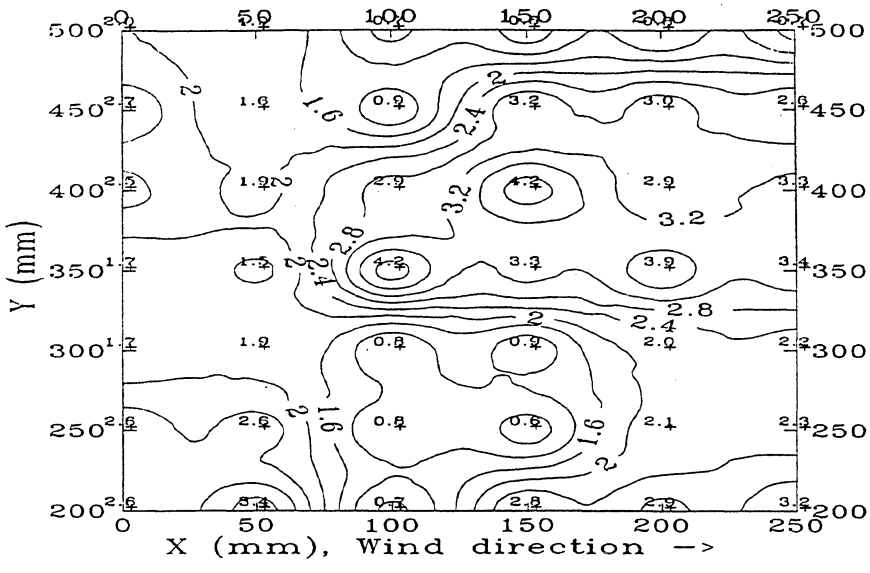
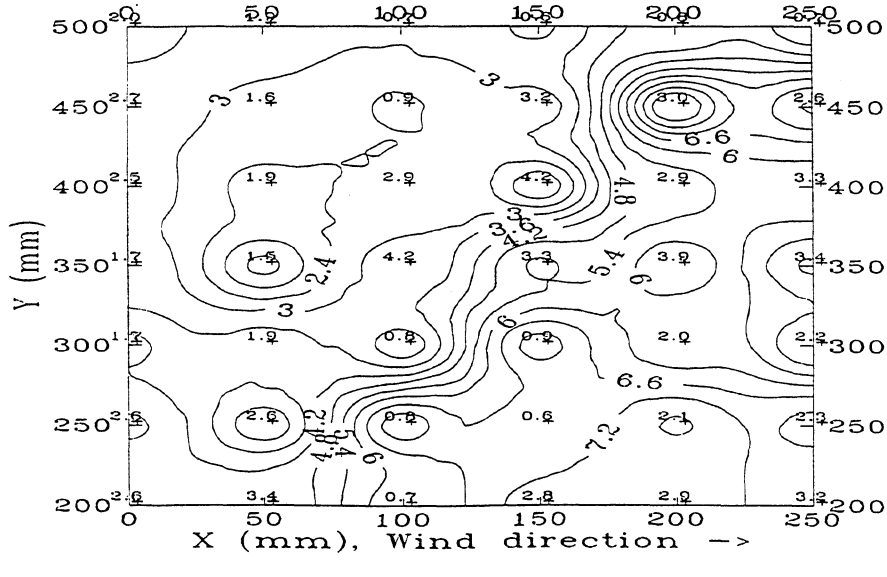


Figure 4. A series of photographs of the fluorescent micro-tufts around the three-dimensional model of the *Myrsine divaricata* plant. The wind speed shown in each photograph is (a) 4 ms^{-1}, (b) 12 ms^{-1} , (c) & (d) 16 ms^{-1}.

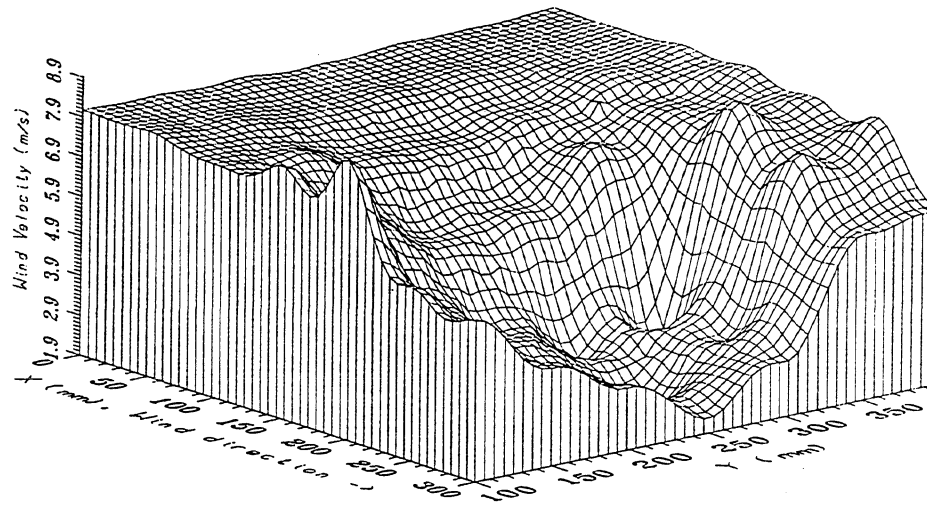


(a)

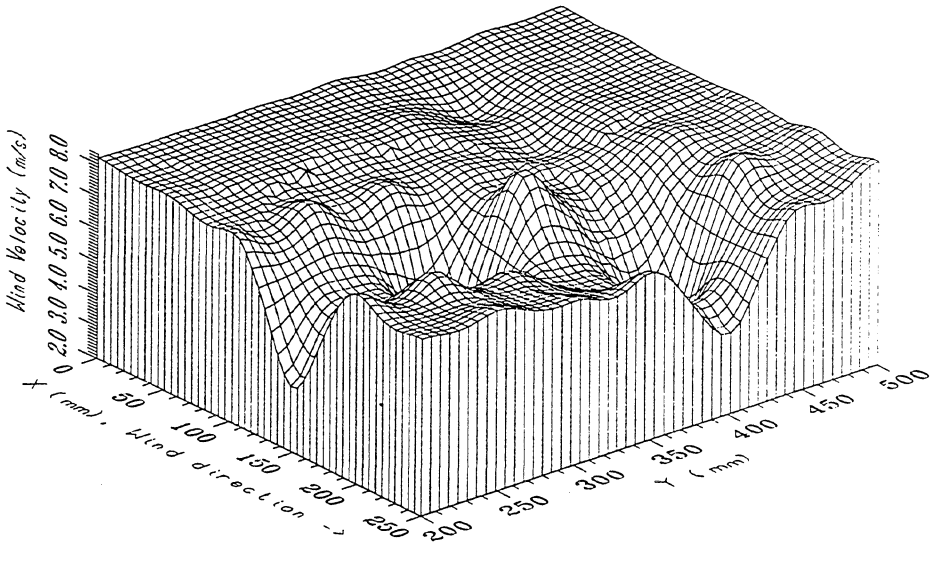


(b)

Figure 5. Normal velocity contour between branches of *Myrsine divaricata* at incident air velocities of (a) 4 ms^{-1} and (b) 8ms^{-1} at various positions about the base of the stem located at ($x = 0$, $y = 0$) The airflow patterns follow the movement of the shrub at the higher wind speed when the plant leans over and the branches bend towards the floor. The wind direction is from left to right along the *x*-axis.

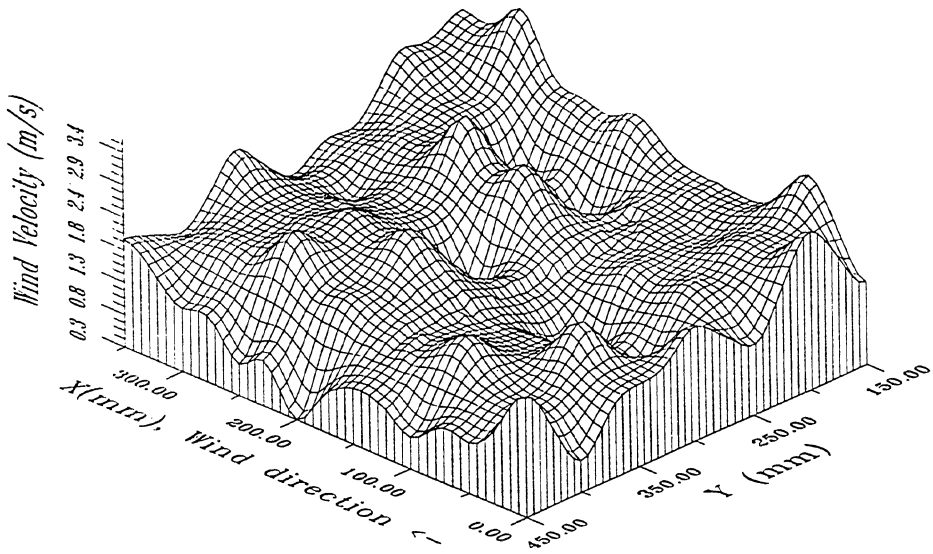


(a)

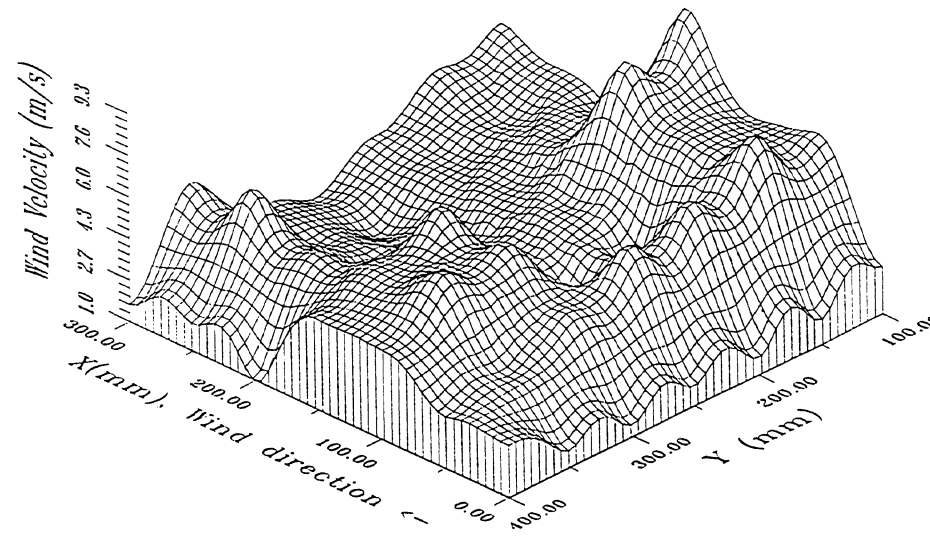


(b)

Figure 6. Topographical horizontal velocity plots for an incident velocity of 8 ms^{-1} illustrating the significant micro-climate detected by (a) measurements collected around the densely branched model of *Coprosma cheesemanii* and (b) measurements around the less densely branched *Pittosporum obcordatum*. The shrubs are located at (x = 0, y = 0) and the wind direction is from left to right along the x-axis.



(a)



(b)

Figure 7. Topographical velocity plots illustrating the irregular airflow patterns around (a) the zig-zag branches of *Corokia cotoneaster* and (b) those in the case of *Coprosma cheesmanii* with more regular airflow patterns, whose peaks and troughs reflect the positions of the plant's branches. Incident velocities (a) 4ms^{-1} and (b) 8ms^{-1}. The shrubs are located at position (x = 0, y = 0) and the wind direction is right to left along the x-axis.

is essentially zero, so the velocity components in the *y*-direction at right-angles to the wind-tunnel floor reflect the turbulence of the air-stream.

There is an increase in the upward airflow velocities around the centre of the *C. cheesemanii* model, and which are shown by the high peaks in Figure 7(b). This enhancement corresponds to the denser branching in this part of the shrub. The *C. cotoneaster* shows a more even spread of turbulence, because the degree of branching complexity does not increase around the main axis of the plant even though the branches themselves are tangled.

DISCUSSION

From the airflow visualisations around the three-dimensional models of the shrubs, the response of the micro-tufts showed that there were calmer zones within the twiggy central regions of the shrubs and turbulence at the extremities. At the model extremities, the amplitude of the micro-tuft fluctuations usually doubled when the wind speed increased from 4 to 8 ms^{-1}, and they doubled again at wind speeds from 8 to 16 ms^{-1}. The velocities within the calmer zones were reduced down to one-third of the incident value to 1.2 ms^{-1} from 4 ms^{-1} and down to one-sixth at the higher wind speed of 8 ms^{-1}. Overall, there was an average reduction to about 75% of the value of the incident wind speeds.

Measurement of the wind velocities showed that there was a general increase in the airflow complexity as the wind speed increased. This is illustrated in the velocity-contour plots shown in Figure 5 for flow around a *M. divaricata* model at incident speeds of 4 and 8 ms^{-1}. This complexity includes both the appearance of multiple wakes, with reduced velocity zones, and an enhancement of turbulence. The movement and oscillation of branches at the higher wind speeds probably induce secondary eddying to give an intricate overall velocity field throughout.

The denser branching on the *C. cheesemanii* and *C. cotoneaster* models appeared to cause a greater region of lower velocities within the branches, as illustrated in the surface charts of their velocities plotted in Figure 6. On the other hand, regularly spaced or positioned branches (present in the *C. cheesemanii* and *P. obcordatum* shrubs) produced uniformly spaced peaks and troughs in the airflow patterns reflecting the positions of their branches. This behaviour may also be seen in the surface charts shown in Figure 7.

A comparison of the behaviour of the shrubs at wind velocities greater than or equal to 12 m s^{-1} to that of the three-dimensional models showed that the shrubs were very flexible because they were young and had been grown in a protected environment. By leaning over and folding their branches up, the shrubs became more densely branched, therefore increasing the self-protection within the plants. It was observed that the plants took several minutes to recover from their folded position. An investigation into this observation showed that this period of time was dependent on the time for decay when the fan was shut off, not directly to the wind magnitude as had been expected.

Overall, the results from this preliminary research support an aspect of the climate hypothesis for the evolution of divaricate plants. From the velocity measurements, it appears that the tangled branch structures moderate the incidental wind. This shelter should provide a more favourable climate for leaf growth in the central regions of the plants as noted by Kelly (1994). Moreover, Kelly & Ogle (1990) have found enhanced relative humidities within divaricate shrubs which is consistent with the reduced wind velocities shown here. The leaves in the central regions should also be in better condition than those at the extremities of the plants because of this sheltering effect. There was no evidence of preferred positions, nor signs of improved health in the leaves of the shrubs used in these tests; but it was observed on the *M. divaricata* shrub that new growth of leaves was established initially in the centre of the shrub, before any growth appeared in the outer branch network.

Other observations gave a possible indication on the relative rate of transpiration of the four test plants. The shrubs that had the greater foliage (*C. cheesemanii, M. divaricata* and *C. cotoneaster*) also had the denser or more tangled branching, and these plants appeared to draw more moisture from the soil in their pots than the less tangled and open *P.*

obcordatum specimen. More tangled branching provides a greater reduction in the incidental wind flow and a greater inhibition of convective loss from the centre of the plant. Further tests are needed to determine the impact of this sheltering on overall transpiration rates.

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